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Method for the Identification of Agents for Use in the Treatment of Alzheimer's Disease

Statement as to Rights to Inventions Made Under Federally-Sponsored Research and Development

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Background of the Invention

Polymers of Abeta (Aβ), the 4.3 kD, 39-43 amino acid peptide product of the transmembrane protein, amyloid protein precursor (APP), are the main components extracted from the neuritic and vascular amyloid of Alzheimer's disease (AD) brains. Aβ deposits are usually most concentrated in regions of high neuronal cell death, and may be present in various morphologies, including amorphous deposits, neurophil plaque amyloid, and amyloid congophilic angiopathy (Masters, C.L., *et al., EMBO J. 4*:2757 (1985); Masters, C.L. *et al., Proc. Natl. Acad. Sci. USA 82*: 4245 (1985)). Growing evidence suggests that amyloid deposits are intimately associated with the neuronal demise that leads to dementia in the disorder.

The presence of an enrichment of the 42 residue species of Aβ in these deposits suggests that this species is more pathogenic. The 42 residue form of Aβ ($A\beta_{1-42}$), while a minor component of biological fluids, is highly enriched in amyloid, and genetic studies strongly implicate this protein in the etiopathogenesis of AD. Amyloid deposits are decorated with inflammatory response proteins, but biochemical markers of severe oxidative stress such as peroxidation adducts, advanced glycation end-products, and protein cross-linking are seen in proximity to the lesions. To date, the cause of Aβ deposits is unknown, although it is believed that preventing these deposits may be a means of treating the disorder.

When polymers of Aβ are placed into culture with rat hippocampal neurons, they are neurotoxic (Kuo, Y-M., *et al., J. Biol. Chem. 271*:4077-81 (1996); Roher, A.E., *et al., Journal of Biological Chemistry 271*:20631-20635 (1996)). The mechanism underlying the formation of these neurotoxic polymeric Aβ species remains unresolved. The overexpression of Aβ alone cannot sufficiently explain amyloid formation, since the concentration of Aβ required for precipitation is not physiologically plausible. That alterations in the neurochemical environment are required for amyloid formation is indicated by its solubility in neural phosphate buffer at concentrations of up to 16 mg/ml (Tomski, S. & Murphy, R.M. *Archives of Biochemistry and Biophysics 294*:630 (1992)), biological fluids such as cerebrospinal fluid (CSF) (Shoji, M., Golde *et al.* (1992); Seubert, P. (1992); Haass *et al.* (1992)) and in the plaque-free brains of Down's syndrome patients (Teller, J.K., *et al., Nature Medicine 2*:93-95 (1996)).

Studies into the neurochemical vulnerability of Aβ to form amyloid have suggested altered zinc and [H^+] homeostasis as the most likely explanations for amyloid deposition. Aβ is rapidly precipitated under mildly acidic conditions *in vitro* (pH 3.5-6.5) (Barrow C.J. & Zagorski M.G., *Science 253*:179-182 (1991); Fraser, P.E., *et al., Biophys. J. 60*:1190-1201 (1991); Barrow, C.J., *et al., J. Mol. Biol. 225*:1075-1093 (1992); Burdick, D., *J. Biol. Chem.* 267:546-554 (1992); Zagorski, M.G. and Barrow, C.J., *Biochemistry 31*:5621-5631 (1992); Kirshenbaum, K. and Daggett, V., *Biochemistry 34*:7629-7639 (1995); Wood, S.J., *et al., J. Mol. Biol. 256*:870-877 (1996)). Recently, it has been shown that the presence of certain biometals, in particular redox inactive Zn^{2+} and, to a lesser extent, redox active Cu^{2+} and Fe^{2+}, markedly increases the precipitation of soluble Aβ (A.T. Bush *et al., J. Biol. Chem. 268*:16109 (1993); A.I. Bush *et al., J. Biol. Chem. 269*:12152 (1994); A.I. Bush *et al., Science 265*:1464 (1994); A.I. Bush, *et al., Science 268*:1921 (1995)). At physiological pH, $A\beta_{1\text{-}40}$ specifically and saturably binds Zn^{2+}, manifesting high affinity binding (K_D = 107 nM) with a 1:1 (Zn^{2+}:Aβ) stoichiometry, and low affinity binding (K_D = 5.2 μM) with a 2:1

stoichiometry. However, the complete reversibility of Zn-induced $A\beta_{1-40}$ aggregation in the presence of divalent metal ion chelating agents suggests that zinc binding is a reversible, normal function of Aβ and implicates other neurochemical mechanisms in the formation of amyloid. A process involving irreversible Aβ aggregation, such as the crosslinking of Aβ monomers, in the formation of polymeric species of Aβ that are present in amyloid plaques is thus a more plausible explanation for the formation of neurotoxic polymeric Aβ species.

The reduction by APP of copper (II) to copper (I) may lead to irreversible Aβ aggregation and crosslinking. This reaction may promote an environment that would enhance the production of hydroxyl radicals, which may contribute to oxidative stress in AD (Multhaup, G., *et al., Science 271*:1406-1409 (1996)). A precedence for abnormal Cu metabolism already exists in the neurodegenerative disorders of Wilson's disease, Menkes' syndrome and possibly familial amyotrophic lateral sclerosis (Tanzi, R.E. *et al., Nature Genetics 5*:344 (1993); Bull, P.C., *et al., Nature Genetics 5*:327-x (1993); Vulpe, C., *et al., Nature Genetics 3*:7 (1993); Yamaguchi, Y., *et al., Biochem. Biophys. Res. Commun. 197*:271 (1993); Chelly, J. *et al., Nature Genetics 3*:14 (1993); Wang, D. & Munoz, D.G., *J. Neuropathol. Exp. Neurol. 54*:548 (1995); Beckman, J.S., *et al., Nature 364*:584 (1993); Hartmann, H.A. & Evenson, M.A., *Med. Hypotheses 38*:75 (1992)).

Although much fundamental pathology, genetic susceptibility and biology associated with AD is becoming clearer, a rational chemical and structural basis for developing effective drugs to prevent or cure the disease remains elusive. While the genetics of the disorder indicates that the metabolism of Aβ is intimately associated with the etiopatholgenesis of the disease, drugs for the treatment of AD have so far focused on "cognition enhancers" which do not address the underlying disease processes.

Summary of the Invention

The invention relates to a method for the identification of an agent to be used in the treatment of AD, wherein the agent is capable of altering the production of Cu(I) by Aβ, the method comprising:

(a) adding Cu(II) to a first Aβ sample;

(b) allowing the first sample to incubate for an amount of time sufficient to allow said first sample to generate Cu(I);

(c) adding Cu(II) to a second Aβ sample, the second sample additionally comprising a candidate pharmacological agent;

(d) allowing the second sample to incubate for the same amount of time as the first sample;

(e) determining the amount of Cu(I) produced by the first sample and the second sample; and

(f) comparing the amount of Cu(I) produced by the first sample to the amount of Cu(I) produced by the second sample;

whereby a difference in the amount of Cu(I) produced by the first sample as compared to the second sample indicates that the candidate pharmacological agent has altered the production of Cu(I) by Aβ.

In a preferred embodiment, the amount of Cu(I) present in said first and said second sample is determined by

(a) adding a complexing agent to said first and said second sample, wherein said complexing agent is capable of combining with Cu(I) to form a complex compound, wherein said complex compound has an optimal visible absorption wavelength;

(b) measuring the absorbancy of said first and said second ~~sample; and~~

(c) calculating the concentration of Cu(I) in said first and said second sample using the absorbancy obtained in step (b).

In a more preferred embodiment, the complexing agent is bathocuproinedisulfonic (BC) anion. The concentration of Cu^+ produced by Aβ may then be calculated on the basis of the absorbance of the sample at about 478 nm to about 488 nm, more preferable about 480 to about 486 nm, and most preferably about 483 nm.

In another aspect, the invention relates to a method for the identification of an agent to be used in the treatment of AD, wherein said agent is capable of altering the production of Fe(II) by Aβ, said method comprising:

(a) adding Fe(III) to a first Aβ sample;

(b) allowing said first sample to incubate for an amount of time sufficient to allow said first sample to generate Cu^+;

(c) adding Fe(III) to a second Aβ sample, said second sample additionally comprising a candidate pharmacological agent;

(d) allowing said second sample to incubate for the same amount of time as said first sample;

(e) determining the amount of Fe(II) produced by said first sample and said second sample; and

(f) comparing the amount of Fe(II) present in said first sample to the amount of Fe(II) present in said second sample;

whereby a difference in the amount of Fe(II) present in said first sample as compared to said second sample indicates that said candidate pharmacological agent has altered the production of Fe(II) by Aβ.

In a preferred embodiment, the amount of Fe(II) present is determined by using a spectrophotometric method analagous to that used for the determination of Cu(I), above. In this method, the complexing agent is batho-phenanthrolinedisulfonic (BP) anion. The concentration of Fe^{2+}-BP produced by Aβ may then be calculated on the basis of the absorbance of the sample at about 530 to about 540 nm, more preferably about 533 nm to about 538 nm, and most preferably about 535 nm.

In yet another aspect, the invention relates to a method for the identification of an agent to be used in the treatment of AD, wherein said agent is capable of altering the production of H_2O_2 by Aβ, said method comprising:

(a) adding Cu(II) or Fe(III) to a first Aβ sample;

(b) allowing said first sample to incubate for an amount of time sufficient to allow said first sample to generate H_2O_2;

(c) adding Cu(II) or Fe(III) to a second Aβ sample, said second sample additionally comprising a candidate pharmacological agent;

(d) allowing said second sample to incubate for the same amount of time as said first sample;

(e) determining the amount of H_2O_2 produced by said first sample and said second sample; and

(f) comparing the amount of H_2O_2 present in said first sample to the amount of H_2O_2 present in said second sample;

whereby a difference in the amount of H_2O_2 present in said first sample as compared to said second sample indicates that said candidate pharmacological agent has altered the production of H_2O_2 by Aβ.

In a preferred embodiment, the determination of the amount of H_2O_2 present in said first and said second sample is determined by

(a) adding catalase to a first aliquot of said first sample obtained in step (a) of claim 1 in an amount sufficient to break down all of the H_2O_2 generated by said sample;

(b) adding TCEP, in an amount sufficient to capture all of the H_2O_2 present in said samples, to

(i) said first aliquot

(ii) a second aliquot of said first sample obtained in step (a) of claim 1; and

(iii) said second sample obtained in step (b) of claim 1;

(c) incubating the samples obtained in step (b) for an amount of time sufficient to allow the TCEP to capture all of the H_20_2;

(d) adding DTNB to said samples obtained in step (c);

(e) incubating said samples obtained in step (d) for an amount of time sufficient to generate TMB;

(f) measuring the absorbancy at about 407to about 417 nm of said samples obtained in step (e); and

(g) calculating the concentration of H_2O_2 in said first and said second sample using the absorbancies obtained in step (f). In a preferred embodiment, the absorbancy of TMB is measured at about 412 nm.

In another aspect, the invention relates to a method for the identification of an agent to be used in the treatment of AD, wherein said agent is capable of decreasing the production of O_2- by Aβ, said method comprising:

(a) adding Aβ and to a first buffer sample having an O_2 tension greater than 0;

(b) allowing said first sample to incubate for an amount of time sufficient to allow said first sample to generate O_2-;

(c) adding Aβ and a candidate pharmacological agent to a second buffer sample having an O_2 tension greater than 0;

(d) allowing said second sample to incubate for the same amount of time as said first sample;

(e) determining the amount of O_2- produced by said first sample and said second sample; and

(f) comparing the amount of O_2- present in said first sample to the amount of O_{2}- present in said second sample;

whereby a difference in the amount of O_2- present in said first sample as compared to said second sample indicates that said candidate pharmacological agent has altered the production of O_2- by Aβ. In a preferred embodiment, the Aβ used is $A\beta_{1-42}$.

Because the ability of Aβ to generate H_2O_2 from O_2- may in many instances be beneficial, in a prefered embodiment, the invention also relates to a method for the identification of an agent to be used in the treatment of AD,

wherein said agent is capable of interfering with the interaction of O_2 and Aβ to produce O_2-, without interfering with the SOD-like activity of Aβ, said method comprising:

(a) identifying an agent capable of decreasing the production of O_2- by Aβ; and

(b) determining the ability of said agent to alter the SOD-like activity of Aβ. In a preferred embodiment, the determination of the ability of said agent to alter the SOD-like activity of Aβ is made by determining whether Aβ is capable of catalytically producing Cu(I), Fe(II) or H_2O_2.

Brief Description of the Figures

Figure 1 is a graph showing the proportion of soluble $A\beta_{1-40}$ remaining following centrifugation of reaction mixtures.

Figures 2A, 2B and 2C: Figure 2A is a graph showing the proportion of soluble $A\beta_{1-40}$ remaining in the supernatant after incubation with various metal ions. Figure 2B is a graph showing a turbidometric analysis of pH effect on metal ion-induced $A\beta_{1-40}$ aggregation. Figure 2C is a graph showing the proportion of soluble $A\beta_{1-40}$ remaining in the supernatant after incubation with various metal ions, where high metal ion concentrations were used.

Figure 3 is a graph showing a competition analysis of $A\beta_{1-40}$. binding to Cu^{2+}.

Figures 4A, 4B and 4C: Figure 4A is a graph showing the proprtion of soluble $A\beta_{1-40}$ remaining in the supernatant following incubation at various pHs in PBS ± Zn^{2+}. Figure 4B is a graph showing the proprtion of soluble $A\beta_{1-40}$ remaining in the supernatant following incubation at various pHs with different Cu^{2+} concentrations. Figure 4C is a graph showing the relative aggregation ofnM concentrations of $A\beta_{1-40}$ at pH 7.4 and 6.6 with different Cu^{2+} concentrations.

Figures 5A and 5B: Figure 5A is a graph showing a turbidometric analysis of Cu^{2+}-induced $A\beta_{1-40}$ aggregation at pH 7.4 reversed by successive cycles of

chelator. Figure 5B is a graph showing a turbidometric analysis of the reversibility of Cu^{2+}-induced $A\beta_{1-40}$ aggregation as the pH cycles between 7.4 and 6.6.

Figure 6 shows the amino acid sequence of $APP_{669-716}$ near $A\beta_{1-42}$. Rat Aβ is mutated (R5G, Y10F, H13R; bold). Possible metal-binding residues are underlined.

Figure 7 is a graph showing the effects of pH, Zn^{2+} or Cu^{2+} upon Aβ formation.

Figure 8 is a western blot showing the extraction of Aβ from post-mortem brain tissue.

Figure 9 is a western blot showing Aβ crosslinking by copper.

Figure 10 is a graph showing Cu(I) generation by Aβ.

Figure 11 is a graph showing H_2O_2 production by Aβ.

Figure 12 is a model for free radical and amyloid formation in Alzheimer's disease.

Detailed Description of the Preferred Embodiments

Definitions

In the description that follows, a number of terms are utilized extensively. In order to provide a clear and consistent understanding of the specification and claims, including the scope to be given such terms, the following definitions are provided.

Aβ peptide is also known in the art as Aβ, β protein, β-A4 and A4. In the present invention, the Aβ peptide may be comprised of peptides $A\beta_{1-39}$, $A\beta_{1-40}$, $A\beta_{1-41}$, $A\beta_{1-42}$, and $A\beta_{1-43}$. The most preferred embodiment of the invention makes use of $A\beta_{1-40}$. However, any of the Aβ peptides may be employed according to the present invention. The sequence of Aβ peptide is found in C. Hilbich *et al.*, *J. Mol. Biol. 228*:460-473 (1992).

Amyloid as is commonly known in the art, and as is intended in the present specification, is a form of aggregated protein.

Aβ Amyloid is an aggregated Aβ peptide. It is found in the brains of patients afflicted with AD and DS and may accumulate following head injuries.

Physiological solution as used in the present specification means a solution which comprises compounds at physiological pH, about 7.4, which closely represents a bodily or biological fluid, such as CSF, blood, plasma, et cetera.

Zinc, unless otherwise indicated, means salts of zinc, i.e., Zn^{2+} in any form, soluble or insoluble.

Copper(II), unless otherwise indicated, means salts of Cu(II), i.e., Cu^{2+} in any form, soluble or insoluble.

Copper(I), unless otherwise indicated, means salts of Cu(I), i.e., Cu^{+} in any form, soluble or insoluble.

Biological fluid means fluid obtained from a person or animal which is produced by said person or animal. Examples of biological fluids include but are not limited to cerebrospinal fluid (CSF), blood, serum, and plasma. In the present invention, biological fluid includes whole or any fraction of such fluids derived by purification by any means, *e.g.*, by ultrafiltration or chromatography.

The aim of the present invention is to clarify both the factors which contribute to the neurotoxicity of Aβ polymers and the mechanism which underlies their formation. These findings can then be used to (i) identify agents that can be used to decrease the neurotoxicity of Aβ, as well as the formation of Aβ polymers, and (ii) utilize such agents to develop methods of preventing, treating or alleviating the symptoms of AD.

The present invention relates to the unexpected discovery that Aβ peptides directly produce oxidative stress through the generation of abundant reactive oxygen species (ROS), which include hydroxyl radical (OH·) and hydrogen peroxide (H_2O_2). The production of ROS occurs by a metal (Cu, Fe) dependant,

pH mediated mechanism, wherein the reduction of Cu(II) to Cu(I), or Fe(III) to Fe(II), is catalyzed by Aβ. Aβ is highly efficient at reducing Cu(II) and Fe(III).

All the redox properties of $A\beta_{1-40}$ (the most abundant form of soluble Aβ) are exaggerated in $A\beta_{1-42}$. Additionally, $A\beta_{1-42}$, but not $A\beta_{1-40}$, recruits O_2 into spontaneous generation of another ROS, O_2-, which also occurs in a metal-dependent manner. The exaggerated redox activity of $A\beta_{1-42}$ and its enhanced ability to generate ROS are likely to be the explanation for its neurotoxic properties. Interestingly, the rat homologue of Aβ, which has 3 substitutions that have been shown to attenuate zinc binding and zinc-mediated precipitation. The rat homologue also exhibits less redox activity than its human counterpart. This may explain why the rat is exceptional in that it is the only mammal that does not exhibit amyloid pathology with age. All other mammals analyzed to date possess the human Aβ sequence.

The sequence of ROS generation by Aβ follows the pathway of superoxide-dismutation, which leads to hydrogen peroxide production in a Cu/Fe-dependent manner. After forming H_2O_2, the hydroxyl radical (OH·) is rapidly formed by a Fenton reaction with the Fe or Cu that is present, even when these metals are only at trace concentrations. The OH· radical is very reactive and rapidly attacks the Aβ peptide, causing it to cross-link and polymerize. This is very likely to be the chemical mechanism that causes the covalent cross-linking that is seen in mature plaque amyloid. Importantly, the redox activity of Aβ is not attenuated by precipitation of the peptide, suggesting that, *in vivo*, amyloid deposits could be capable of generating ROS *in situ* on an enduring basis. This suggests that the major source of the oxidative stress in an AD-affected brain are amyloid deposits.

A model for free radical and amyloid formation in AD is shown in Fig. 12. The proposed mechnism is explained as follows.

(1) Soluble and precipitated Aβ species possess superoxide dismutase (SOD)-like activity. Superoxide (O_2^-), the substrate for the dismutation, is generated both by spillover from mitochondrial respiratory metabolism, and by

$A\beta_{1-42}$ itself (see FIG. 11). Aβ-mediated dismutation produces hydrogen peroxide (H_2O_2), requiring Cu(II) or Fe(III), which are reducted during the reaction. Since H^+ is required for H_2O_2 production, an acidotic environment will increase the reaction.

(2) H_2O_2 is relatively stable, and freely permeable across cell membranes. Normally, it will be broken down by intercellular catalase or glutathione peroxidase.

(3) In aging and AD, levels of H_2O_2 are high, and catalase and peroxidase activities are low. If H_2O_2 is not completely catalyzed, it will react with reduced Cu(I) and Fe(II) in the vicinity of Aβ to generate the highly reduced Cu(I) and Fe(II) in the vicinity of Aβ to generate the highly reactive hydroxyl radical (OH•) by Fenton chemistry.

(4) OH• engenders a non-specific stress and inflammatory response in local tissue. Among the neurochemicals that are released from microglia and possibly neurons in the response are Zn(II), Cu(II) and soluble Aβ. Familial AD increases the likelihood that $A\beta_{1-42}$ will be released at this point. Local acidosis is also part of the stress/inflammatory response. These factors combine to make Aβ precipitate and accumulate, presumably so that it may function *in situ* as an SOD, since these factors induce reversible polymerization. Hence, more soluble Aβ species decorate the perimeter of the accumulating plaque deposits.

(5) If Aβ encounters OH•, it will covalently cross-link during the oligomerization process, making it a more difficult accumulation to resolubilize, and leading to the formation of SDS-resistant oligomers characteristic of plaque amyloid.

(6) If $A\beta_{1-42}$ accumulates, it has the property of recruiting O_2 as a substrate for the abundant production of O_2^- by a process that is still not understood. Since O_2 is abundant in the brain, $A\beta_{1-42}$ is responsible for setting off a vicious cycle in which the accumulation of covalently linked Aβ is a product of the unusual ability of Aβ to reduce O_2, and feed an abundant substrate (O_2^-) to itself for dismutation, leading to OH• formation. The production of abundant free

radicals by the accumulating amyloid may further damage many systems including metal regulatory proteins, thus compounding the problem. This suggests that the major source of the oxidative stress in an AD-affected brain are amyloid deposits.

The metal-dependent chemistry of Aβ-mediated superoxide dismutation is reminiscent of the activity of superoxide dismutase (SOD). Interestingly, mutations of SOD cause amyotrophic lateral sclerosis, another neurodegenerative disorder. SOD is predominantly intracellular, whereas Aβ is constitutively found in the extracellular spaces where it accumulates. Investigation of Aβ by laser flash photolysis confirmed the peptide's SOD-like activity, suggesting that Aβ may be an anti-oxidant under physiological circumstances. Since H_2O_2 has been shown to induce the production of Aβ, the accumulation of Aβ in AD may reflect a response to an oxidant stress paradoxically caused by Aβ excess. This may cause and, in turn, be compounded by, damage to the biometal homeostatic mechanisms in the brain environment.

Thus, it has recently been discovered (i) that much of the Aβ aggregate in AD-affected brain is held together by zinc and copper, (ii) that Aβ peptides exhibit Fe/Cu-dependent redox activity similar to that of SOD, (iii) that $A\beta_{1-42}$ is especially redox reactive and has the unusual property of reducing O_2 to O_2^-, and (iv) that deregulation of Aβ redox reactivity causes the peptide to conveniently polymerize. Since these reactions must be strongly implicated in the pathogenetic events of AD, they offer promising targets for therapeutic drug design.

The discovery that Aβ can generate H_2O_2 and Cu(I), both of which are associated with neurotoxic effects, offers an explanation for the neurotoxicity of Aβ polymers. These findings suggest that it may be possible to lessen the neurotoxicity of Aβ by controlling factors which alter the concentrations of Cu(I) and ROS, including hydrogen peroxide, being generated by accumulated and soluble Aβ. It has been discovered that manipulation of factors such as zinc, copper, and pH can result in altered Cu(I) and H_2O_2 production by Aβ. Therefore, agents identified as being useful for the adjustment of the pH and

levels of zinc and copper of the brain interstitium can be used to adjust the concentration of Cu(I) and H_2O_2, and can therefore be used to reduce the neurotoxic burden. Such agents will thus be a means of treating Alzheimer's disease.

Thus, one object of the present invention is to provide a method for the identification of agents to be used in the treatment of AD. As may be understood by reference to the Examples below, agents to be used in the treatment of AD include:

(a) agents that reduce the amount of Cu(I) or Fe(II) produced by Aβ;

(b) agents that promote or inhibit the production of hydrogen peroxide by Aβ;

(c) agents that inhibit the production of O_2- by Aβ;

(d) agents that inhibit the production of OH·.

Of course, as aggregation and especially crosslinking of Aβ contributes to the neurotoxic burden, agents which have been identifed to have the activities listed above may then also be subjected to tests which determine if an agent is capable of inhibiting oligomerization by Aβ (see Example 1).

Agents identified as having the above-listed activities may then be tested for their ability to reduce the neurotoxicity of both soluble and crosslinked Aβ.

Thus, in one aspect, the invention relates to a method for the identification of an agent to be used in the treatment of AD, wherein the agent is capable of altering, and preferably decreasing, the production of Cu(I) by Aβ, the method comprising:

(a) adding Cu(II) to a first Aβ sample;

(b) allowing the first sample to incubate for an amount of time sufficient to allow said first sample to generate Cu(I);

(c) adding Cu(II) to a second Aβ sample, the second sample additionally comprising a candidate pharmacological agent;

(d) allowing the second sample to incubate for the same amount of time as the first sample;

(e) determining the amount of Cu(I) produced by the first sample and the second sample; and

(f) comparing the amount of Cu(I) produced by the first sample to the amount of Cu(I) produced by the second sample;

whereby a difference in the amount of Cu(I) produced by the first sample as compared to the second sample indicates that the candidate pharmacological agent has altered the production of Cu(I) by Aβ. Of course, where the amount of Cu(I) is lower in the second sample than in the first sample, this will indicate that the agent has decreased Cu(I) production.

In a preferred embodiment, the amount of Cu(I) present in said first and said second sample is determined by

(a) adding a complexing agent to said first and said second sample, wherein said complexing agent is capable of combining with Cu(I) to form a complex compound, wherein said complex compound has an optimal visible absorption wavelength;

(b) measuring the absorbancy of said first and said second sample; and

(c) calculating the concentration of Cu(I) in said first and said second sample using the absorbancy obtained in step (b).

In a more preferred embodiment, the complexing agent is bathocuproinedisulfonic (BC) anion. The concentration of Cu^+ produced by Aβ may then be calculated on the basis of the absorbance of the sample at about 478 nm to about 488 nm, more preferable about 480 to about 486 nm, and most preferably about 483 nm.

In an even more preferred embodiment, the above-described method may be preformed in a microtiter plate, and the absorbancy measurement is performed by a plate reader, thus allowing large numbers of candidate pharmacological compounds to be tested simultaneously.

In another aspect, the invention relates to a method for the identification of an agent to be used in the treatment of AD, wherein said agent is capable of

altering, and preferably decreasing, the production of Fe(II) by Aβ, said method comprising:

(a) adding Fe(III) to a first Aβ sample;

(b) allowing said first sample to incubate for an amount of time sufficient to allow said first sample to generate Cu^+;

(c) adding Fe(III) to a second Aβ sample, said second sample additionally comprising a candidate pharmacological agent;

(d) allowing said second sample to incubate for the same amount of time as said first sample;

(e) determining the amount of Fe(II) produced by said first sample and said second sample; and

(f) comparing the amount of Fe(II) present in said first sample to the amount of Fe(II) present in said second sample;

whereby a difference in the amount of Fe(II) present in said first sample as compared to said second sample indicates that said candidate pharmacological agent has altered the production of Fe(II) by Aβ. Of course, where the amount of Fe(II) is lower in the second sample than in the first sample, this will indicate that the agent has decreased Fe(II) production.

In a preferred embodiment, the amount of Fe(II) present is determined by using a spectrophotometric method analagous to that used for the determination of Cu(I), above. In this method, the complexing agent is batho-phenanthrolinedisulfonic (BP) anion. The concentration of Fe^{2+}-BP produced by Aβ may then be calculated on the basis of the absorbance of the sample at about 530 to about 540 nm, more preferably about 533 nm to about 538 nm, and most preferably about 535 nm.

In an even more preferred embodiment, the above-described method may be preformed in a microtiter plate, and the absorbancy measurement is performed by a plate reader, thus allowing large numbers of candidate pharmacological compounds to be tested simultaneously.

In yet another aspect, the invention relates to a method for the identification of an agent to be used in the treatment of AD, wherein said agent is capable of altering the production of H_2O_2 by Aβ, said method comprising:

(a) adding Cu(II) or Fe(III) to a first Aβ sample;

(b) allowing said first sample to incubate for an amount of time sufficient to allow said first sample to generate H_2O_2;

(c) adding Cu(II) or Fe(III) to a second Aβ sample, said second sample additionally comprising a candidate pharmacological agent;

(d) allowing said second sample to incubate for the same amount of time as said first sample;

(e) determining the amount of H_2O_2 produced by said first sample and said second sample; and

(f) comparing the amount of H_2O_2 present in said first sample to the amount of H_2O_2 present in said second sample;

whereby a difference in the amount of H_2O_2 present in said first sample as compared to said second sample indicates that said candidate pharmacological agent has altered the production of H_2O_2 by Aβ. As will be understood by one of ordinary skill in the art, this method may be used to detect agents which decrease the amount of H_2O_2 produced (in which case the amount of H_2O_2 will be lower in the second sample than in the first sample), or to increase the amount of H_2O_2 produced (in which case the amount of H_2O_2 will be lower in the first sample than in the second sample).

In a preferred embodiment, the determination of the amount of H_2O_2 present in said first and said second sample is determined by

(a) adding catalase to a first aliquot of said first sample obtained in step (a) of claim 1 in an amount sufficient to break down all of the H_2O_2 generated by said sample;

(b) adding TCEP, in an amount sufficient to capture all of the H_2O_2 generated by said samples, to

(i) said first aliquot

(ii) a second aliquot of said first sample obtained in step (a) of claim 1; and

(iii) said second sample obtained in step (b) of claim 1;

(c) incubating the samples obtained in step (b) for an amount of time sufficient to allow the TCEP to capture all of the H_20_2;

(d) adding DTNB to said samples obtained in step (c);

(e) incubating said samples obtained in step (d) for an amount of time sufficient to generate TMB;

(f) measuring the absorbancy at about 407to about 417 nm of said samples obtained in step (e); and

(g) calculating the concentration of H_2O_2 in said first and said second sample using the absorbancies obtained in step (f). In a preferred embodiment, the absorbancy of TMB is measured at about 412 nm.

In a preferred embodiment, the above-described method is performed in a microtiter plate, and the absorbancy measurement is performed by a plate reader, thus making it possible to screen large numbers of candidate pharmacological agent simultaneously.

In another enbodiment, the invention provides a method for the identification of an agent to be used in the treatment of AD, wherein said agent is capable of decreasing the production of O_2- by Aβ, said method comprising:

(a) adding Aβ and to a first buffer sample having an O_2 tension greater than 0;

(b) allowing said first sample to incubate for an amount of time sufficient to allow said first sample to generate O_2-;

(c) adding Aβ and a candidate pharmacological agent to a second buffer sample having an O_2 tension greater than 0;;

(d) allowing said second sample to incubate for the same amount of time as said first sample;

(e) determining the amount of O_2- produced by said first sample and said second sample; and

(f) comparing the amount of O_2- present in said first sample to the amount of O_{2-} present in said second sample;

whereby a difference in the amount of O_2- present in said first sample as compared to said second sample indicates that said candidate pharmacological agent has altered the production of O_2- by Aβ. In a preferred embodiment, the Aβ used is $A\beta_{1-42}$.

Of course, the amount of O_2- produced by Aβmay be measured by any method known to those of ordinary skill in the art. In a preferred embodiment, the determination of the amount of O_2- present in said samples is accomplished by measuring the absorbancy of the sample at about 250 nm.

Because the ability of Aβ to generate H_2O_2 from O_2- may in many instances be beneficial, in a prefered embodiment, the invention also relates to a method for the identification of an agent to be used in the treatment of AD, wherein said agent is capable of interfering with the interaction of O_2 and Aβ to produce O_2-, without interfering with the SOD-like activity of Aβ, said method comprising:

(a) identifying an agent capable of decreasing the production of O_2- by Aβ; and

(b) determining the ability of said agent to alter the SOD-like activity of Aβ. In a preferred embodiment, the determination of the ability of said agent to alter the SOD-like activity of Aβ is made by determining whether Aβ is capable of catalytically producing Cu(I), Fe(II) or H_2O_2. Methods, besides those which are disclosed elsewhere in this application, for determining if Aβ is capable of catalytically producing Cu(I), Fe(II) or H_2O_2 are well known to those of ordinary skill in the art. In particular, the catalytic production of H_2O_2 may be determined by using laser flash photolysis or pulse radiolysis (G. Peters and M.A. J. Rodgers, *Biochim. Biophys. Acta 637*: 43-52 (1981)..

In another aspect, candidate pharmacological agents which have been identified by one or more of the above screening assays can undergo further screening to determine if the agents are capable of altering, and preferably

reducing or eliminating, Aβ-mediated toxicity in cell culture. Such assays include the MTT assay, which measures the reduction of 3-(4,5-dimethylthiazol-2-yl)-2,5, diphenyl tetrazolium bromide (MTT) to a colored formazon (Hansen *et al.*, ~~1989~~ a1). Although alternatives have not been ruled out (see Burdon *et al.*, 1993), the major site of MTT reduction is thought to be at two stages of electron transport, the cytochrome oxidase and ubiquinone of mitochondria (Slater *et al.*, 1963). A second cytotoxic assay is the release of lactic dehydrogenase (LDH) from cells, a measurement routinely used to quantitate cytotoxicity in cultured CNS cells (~~Choi, 1987~~ a2). While MTT measures primarily early redox changes within the cell reflecting the integrity of the electron transport chain, the release of LDH is thought to be through cell lysis. A third assay is visual counting in conjunction with trypan blue exclusion. Other commercially available assays for neurotoxicity, including the Live-Dead assay, may also be used to determine if a candidate compound which alters Cu(I), Fe(II), H_2O_2, OH·, and O_2- production, or alters copper-induced, pH dependent aggregation and crosslinking of Aβ, is also capable of reducing the neurotoxicity of Aβ.

Thus, in another prefered embodiment, the invention relates to a method for the identification of an agent to be used in the treatment of AD, wherein said agent is capable of reducing the toxicity of Aβ, said method comprising:

(a) adding Aβ to a first cell culture;

(b) adding Aβ to a second cell culture, said second cell culture additionally containing a candidate pharmacological agent;

(c) determining the level of neurotoxicity of Aβ in said first and said second samples; and

(d) comparing the level of neurotoxicity of Aβ in said first and said second samples,

whereby a lower neurotoxicity level in said second sample as compared to said first sample indicates that said candidate pharmacological agent has reduced the neurotoxicity of Aβ, and is thereby capable of being used to treat AD.

Assays which can be used to determine the neurotoxicity of a candidate agent include, but are not limited to, the MTT assay and the LDH release assay, as described in Behl *et al.* (*Cell 77*: 817-827 (1994)) and the Live/Dead EukoLight Viability/Cytotoxicity Assay, commercially available from Molecular Probes, Inc. (Eugene, OR).

Cells types which may be used for these neurotoxicity assays include both cancer cells and primary cells, such as rat primary frontal neuronal cells.

Candidate pharmacological agents to be tested in any of the above-described methods will be broad-ranging but can be classified as follows: Candidate pharmacological agents for the alteration of the SOD-like activity of Aβ will be broad-ranging but can be classified as follows:

Agents which modify the availability of zinc or copper for interaction with Aβ: They include chelating agents such as desferrioxamine, but also include amino acids histidine and cysteine which bind free zinc, and are thought to be involved in bringing zinc from the plasma across the blood-brain barrier (BBB). These agents include all classes of specific zinc chelating agents, and combinations of non-specific chelating agents capable of chelating zinc such as EDTA (Edetic acid, N,N'-1,2-Ethane diylbis[N-(carboxymethyl)glycine] or (ethylenedinitrilo)tetraacetic acid, entry 3490 in Merck Index 10th edition) and all salts of EDTA, and/or phytic acid [myo-Inositol hexakis(dihydrogen phosphate), entry 7269 in the Merck Index 10th edition] and phytate salts. Preferred candidate agents within this class include bathocuproine and bathophenanthroline

Miscellaneous: Because there is no precedent for an effective anti-amyloidotic pharmaceutical, it is reasonable to serendipitously try out compounds which may have access to the brain compartment for their ability to inhibit either Cu^+ or H_2O_2 production by Aβ. These compounds include dye compounds, heparin, heparan sulfate, and anti-oxidants, *e.g.*, ascorbate, trolox and tocopherols.

In the present invention, the Aβ used may be any form of Aβ. In a preferred embodiment, the Aβ used is selected from the group consisting of $A\beta_{1-39}$, $A\beta_{1-40}$, $A\beta_{1-41}$, $A\beta_{1-42}$, and $A\beta_{1-43}$. Even more preferably, the Aβ used is $A\beta_{1-40}$ or $A\beta_{1-42}$. The most preferred embodiment of the invention makes use of $A\beta_{1-40}$. The sequence of Aβ peptide is found in C. Hilbich *et al., J. Mol. Biol. 228*:460-473 (1992).

The pH of the various reaction mixtures are preferably close to neutral (about 7.4). The pH, therefore, may range from about 6.6 to about 8, preferably from about 6.6 to about 7.8, and most preferably about 7.4.

Buffers which can be used in the methods of the present invention include, but are not limited to, PBS, Tris-chloride and Tris-base, MOPS, HEPES, bicarbonate, Krebs, and Tyrode's. The concentration of the buffers may be between about 10 mM and about 500 mM. Because of the nature of the assays which are included in the methods of the claimed invention, when choosing a buffer, it must be borne in mind that spontaneous free radical production within a given buffer might interfere with the reactions. For this reason, PBS is the preferred buffer for use in the methods of the invention, although other buffers may be used provided that proper controls are used to correct for the above-mentioned free radical formation of a given buffer.

Cu(II) must be present in the reaction mixture for Aβ to produce Cu^+. Any salt of Cu(II) may be used to satisfy this requirement, including, but not limited to, $CuCl_2$, $Cu(NO_3)_2$, *etc.* Concentrations of copper from at least about 1 μM may be used; most preferable, a copper concentration of about 10 μM is to be included in the reaction mixture.

Similarly, a redox active metal such as Cu(II) or Fe(III) must be present in the reaction mixture for Aβ to catalytically produce H_2O_2. Any salt of Cu(II) may be used to satisfy this requirement, including, but not limited to, $CuCl_2$, $Cu(NO_3)_2$, *etc.* Similarly, and salt of Fe(III) may be used in accordance with the invention, such as $FeCl_3$. Concentrations of copper or iron from at least about 1

μM may be used; most preferably, a copper or iron concentration of about 10 μM is to be included in the reaction mixture.

The present invention may be practiced at temperatures ranging from about 25°C to about 40°C. The preferred temperature range is from about 30°C to about 40°C. The most preferred temperature for the practice of the present invention is about 37°C, *i.e.*, human body temperature.

The production of Cu^+ and H_2O_2 by Aβ peptide occurs at near-instantaneous rate. Hence, the measurement of the concentration of Cu^+ or H_2O_2 produced may be performed by the present methods substantially immediately after the addition of Cu(II) to the Aβ peptide. However, if desired, the reaction may be allowed to proceed longer. In a preferred embodiment of the invention, the reaction is carried out for about 30 minutes.

The invention may also be carried out in the presence of biological fluids, such as the preferred biological fluid, CSF, to closely simulate actual physiological conditions. Of course, such fluids will already contain Aβ, so that where the methods of the invention are to be carried out utilizing a biological fluid such as CSF, no further Aβ peptide will be added to the sample. The biological fluid may be used directly or diluted from about 1:1,000 to about 1:5 fold.

The amount of H_2O_2 , Cu(I) or Fe(II) produced by a sample may be measured by any standard assay for H_2O_2, Cu(I) or Fe(II). For example, the PeroXOquant Qunatitative Peroxide Assay (Pierce, Rockford, IL) may be used to determine the amount of H_2O_2 produced. Fe(II) may be determined using the spectrophotometric method of Linert *et al.* (*Biochim. Biophys. Acta 1316*:160-168 (1996)). Other such methods will be readily apparent to those of ordinary skill in the art.

In a preferred embodiment, the H_2O_2 or Cu^+ produced by the sample is complexed with a complexing agent having an optimal visible absorption wavelength. The amount of H_2O_2 or Cu^+ produced by a sample is then detected using optical spectrophotometry (see Example 2).

In a preferred embodiment, the complexing agent to be used for the determination of the amount of Cu^+ produced is bathocuproinedisulfonic anion (BC), (see Example 2); the complex Cu^+-BC has an optimal visible absorption wavelength of about 483 nm. As is mentioned above, Aβ will produce H_2O_2 and Cu^+almost immediately following the addition of Cu(II) and Zn(II) to the reaction mixture. Thus, BC may be added to the reaction immediately following the addition of Cu(II) and Zn(II) to the Aβ samples. The concentration of BC to be achieved in a sample is between about 10 μM to about 400 μM, more preferably about 75 μM to about 300 μM, and still more preferably about 150 μM to about 275 μM. In the most preferred embodiment, the concentration of BC to be achieved in a sample is about 200 μM. Of course, one of ordinary skill in the art can easily optimize the concentration of BC to be added with no more than routine experimentation.

Where the amount of Fe(II) produced is to be determined, the complexing agent to be used for the determination of the amount of Fe(II) produced is bathophenanthrolinedisulfonic (BP) anion, (see Example 2); the complex Fe^{2+}-BP has an optimal visible absorption wavelength of about 535 nm. As is mentioned above, Aβ will produce H_2O_2 and Fe(II) almost immediately following the addition of Fe(III) and Zn(II) to the reaction mixture. Thus, BP may be added to the reaction immediately following the addition of Fe(III) and Zn(II) to the Aβ samples. The concentration of BP to be achieved in a sample is between about 10 μM to about 400 μM, more preferably about 75 μM to about 300 μM, and still more preferably about 150 μM to about 275 μM. In the most preferred embodiment, the concentration of BP to be achieved in a sample is about 200 μM. Of course, one of ordinary skill in the art can easily optimize the concentration of BP to be added with no more than routine experimentation.

The above-described spectrophotometric assays may be used to determine the concentration of Cu^+ or Fe^{2+}, as is described in Example 2.

Each of the assays of the present invention is ideally suited for the preparation of a kit. Such a kit may comprise a carrier means being

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compartmentalized to receive in close confinement therein one or more container means, such as vials, tubes, and the like, each of said container means comprising one of the separate elements of the assay to be used in the method. For example, there may be provided a container means containing standard solutions of the Aβ peptide or lyophilized Aβ peptide and a container means containing a standard solution or varying amounts of a salt of redox active metal, such as Cu(II) or Fe(III), in any form, *i.e.*, in solution or dried, soluble or insoluble, in addition to further carrier means containing varying amounts and/or concentrations of reagents used in the present methods. For example, solutions to be used for the determination of Cu(I) or Fe(II) as described in Example 2 will include BC anion and BP anion, respectively. Similarly, solutions to be used for the determination of H_2O_2 as described in Example 2 include TCEP and DTNB, as well as catalase (10U/ml). Standard solutions of Aβ peptide preferably have concentrations above about 10 μM, more preferably from about 10 to about 25 μM or if the peptide is provided in its lyophilized form, it is provided in an amount which can be solubilized to said concentrations by adding an aqueous buffer or physiological solution. The standard solutions of analytes may be used to prepare control and test reaction mixtures for comparison, according to the methods of the present invention.

The following examples are provided by way of illustration to further describe certain preferred embodiments of the invention, and are not intended to be limiting of the present invention, unless specified.

Examples

Example 1

Copper-Induced, pH Dependent Aggregation of Aβ

Materials and Methods

a) Preparation of Aβ Stock

Human $Aß_{1-40}$ peptide was synthesized, purified and characterized by HPLC analysis, amino acid analysis and mass spectroscopy by W.M. Keck Foundation Biotechnology Resource Laboratory (Yale University, New Haven, CT). Synthetic Aß peptide solutions were dissolved in trifluoroethanol (30 % in Milli-Q water (Millipore Corporation, Milford, MA)) or 20 mM Hepes (pH 8.5) at a concentration of 0.5-1.0 g/ml, centrifuged for 20 min. at 10 000g and the supernatant (stock $Aß_{1-40}$) used for subsequent aggregation assays on the day of the experiment. The concentration of stock $Aß_{1-40}$ was determined by UV spectroscopy at 214 nm or by Micro BCA protein assay (Pierce, Rockford, IL). The Micro BCA assay was performed by adding 10μl of stock $Aß_{1-40}$ (or bovine serum albumin standard) to 140 μl of distilled water, and then adding an equal volume of supernatant (150μl) to a 96-well plate and measuring the absorbance at 562 nm. The concentration of $Aß_{1-40}$ was determined from the BSA standard curve. Prior to use all buffers and stock solutions of metal ions were filtered though a 0.22 μm filter (Gelan Sciences, Ann Arbor, MI) to remove any particulate matter. All metal ions were the chloride salt, except lead nitrate.

b) Aggregation Assays

$Aß_{1-40}$ stock was diluted to 2.5 μM in 150 mM NaCl and 20 mM glycine (pH 3-4.5), mes (pH 5-6.2) or Hepes (pH 6.4-8.8), with or without metal ions,

incubated (30 min., 37 °C), centrifuged (20 min., 10 000g). The amount of protein in the supernatant was determined by the Micro BCA protein assay as described above.

c) Turbidometric Assays

Turbidity measurements were performed as described by Huang *et al.*, *Journal of Biological Chemistry* (submitted), except $A\beta_{1-40}$ stock was brought to 10 μM (300 μl) in 20 mM HEPES buffer, 150 mM NaCl (pH 6.6, 6.8 or 7.4) with or without metal ions prior to incubation (30 min., 37 °C). To investigate the pH reversibility of Cu^{2+}-induced Aß aggregation, 25 μM $A\beta_{1-40}$ and 25 μM Cu^{2+} were mixed in 67 mM phosphate buffer, 150 mM NaCl (pH 7.4) and turbidity measurements were taken at four 1 min. intervals. Subsequently, 20 μl aliquots of 10 mM EDTA or 10 mM Cu^{2+} were added into the wells alternatively, and, following a 2 min. delay, a further four readings were taken at 1 min. intervals. After the final EDTA addition and turbidity reading, the mixtures were incubated for an additional 30 min. before taking final readings. To investigate the reversibility of pH mediated Cu^{2+}-induced $A\beta_{1-40}$ aggregation, 10 μM $A\beta_{1-40}$ and 30 μM Cu^{2+} were mixed in 67 mM phosphate buffer, 150 mM NaCl (pH 7.4) and an initial turbidity measurement taken. Subsequently, the pH of the solution was successively decreased to 6.6 and then increased back to 7.5. The pH of the reaction was monitored with a microprobe (Lazar Research Laboratories Inc., Los Angeles, CA) and the turbidity read at 5 min. intervals for up to 30 min. This cycle was repeated three times.

d) Immunofiltration Detection of Low Concentrations of $A\beta_{1-40}$ Aggregate

Physiological concentrations of $A\beta_{1-40}$ (8 nM) were brought to 150 mM NaCl, 20 mM HEPES (pH 6.6 or 7.4), 100 nM BSA with $CuCl_2$ (0, 0.1, 0.2, 0.5 and 2 μM) and incubated (30 min., 37°C). The reaction mixtures (200 μl) were

then placed into the 96-well Easy-Titer ELIFA system (Pierce, Rockford, IL) and filtered through a 0.22 μm cellulose acetate filter (MSI, Westboro, MA). Aggregated particles were fixed to the membrane (0.1% glutaraldehyde, 15 min.), washed thoroughly and then probed with the anti-Aß mAB 6E10 (Senetek, Maryland Heights, MI). Blots were washed and exposed to film in the presence of ECL chemiluminescence reagents (Amersham, Buckinghamshire, England). Immunoreactivity was quantified by transmitance analysis of ECL film from the immunoblots.

e) Aß metal-capture ELISA

$Aß_{1-40}$ (1.5 ng/well) was incubated (37°C, 2 hr) in the wells of Cu^{2+} coated microtiter plates (Xenopore, Hawthorne, NJ) with increasing concentrations of Cu^{2+} (1-100 nM) as described by Moir *et al.*, *Journal of Biological Chemistry* (submitted). Remaining ligand binding sites on well surfaces were blocked with 2% gelatin in tris-buffered saline (TBS) (3 hr at 37°C) prior to overnight incubation at room temperature with the anti-Aß mAb 6E10 (Senetek, Maryland Heights, MI). Anti-mouse IgG coupled to horseradish peroxidase was then added to each well and incubated for 3 hr at 37°C. Bound antibodies were detected by a 30 minute incubation with stable peroxidase substrate buffer/3,3',5,5'-Tetramethyl benzidine (SPSB/TMB) buffer, followed by the addition of 2 M sulfuric acid and measurement of the increase in absorbance at 450 nm.

f) Extraction of Aβ from post-mortem brain tissue

Identical regions of frontal cortex (0.5g) from post-mortem brains of individuals with AD, as well as non-AD conditions, were homogenized in TBS, pH 4.7 ±metal chelators. The homogenate was centrifuged and samples of the soluble supernatant as well as the pellet were extracted into SDS sample buffer and assayed for Aβ content by western blotting using monoclonal antibody

(mAb) WO2. The data shows a typical (of n=12 comparisons) result comparing the amount of Aβ extracted into the supernatant phase in AD compared to control (young adult) samples. N,N,N',N'-tetrakis [2-pyridyl-methyl] ethylenediamine (TPEN) (5 μM) allows the visualization of a population of pelletable Aβ that had not previously been recognized in unaffected brain samples (Fig. 8).

g) Aβ cross-linking by copper

Cu^{2+}-induced SDS-resistant oligomerization of Aβ: $A\beta_{1-40}$ (2.5 μM), 150 mM NaCl, 20 mM hepes (pH 6.6, 7.4, 9) with or without $ZnCl_2$ or $CuCl_2$. Following incubation (37°C), aliquots of each reaction (2 ng peptide) were collected at 0 d, 1 d, 3 d and 5 d and western blotted using anti-Aβ monoclonal antibody 8E10. Migration of the molecular size markers are indicated (kDa). The dimer formed under these conditions has been found to be covalently linked. Cu(II) (2-30 μM) induced and covalent oligomerization of peptide. Co-incubation with similar concentrations of Zn(II) accelerates the bridging, but zinc alone has no effect. The antioxidant sodium metabisulphite moderately attenuates the reaction, while ascorbic acid dramatically accelerates Aβ bridging. This suggests reduction of Cu(II) to Cu(I) with the latter mediating covalent bridging of Aβ. Mannitol also abolishes the cross-linking, suggesting that the bridging is mediated by the generation of the hydroxyl radical by a Fenton reaction that recruits Cu(I) (Fig. 9). It should be noted that other means of visualizing and/or determining the presence or absence of crosslinking other than western blot analysis may be used. Such other means include but are not limited to density sedimentation by centrifugation of the samples.

Results

It has previously been reported that Zn^{2+} induces rapid precipitation of Aβ *in vitro* (Bush, A.I., *et al.*, *Science 268*:1921 (1995)). This metal has an abnormal metabolism in AD and is highly concentrated in brain regions where Aβ precipitates. The present data indicate that under very slightly acidic conditions, such as in the lactic acidotic AD brain, Cu^{2+} strikingly induces the precipitation of Aβ through an unknown conformational shift. pH alone dramatically affects Aβ solubility, inducing precipitation when the pH of the incubation approaches the pI of the peptide (pH 5-6). Zinc induces 40-50% of the peptide to precipitate at pH > 6.2, below pH 6.2 the precipitating effects of Zn^{2+} and acid are not summative. At pH ≤ 5, Zn^{2+} has little effect upon Aβ solubility. Cu^{2+} is more effective than Zn^{2+} in precipitating Aβ and even induces precipitation at the physiologically relevant pH 6-7. Copper-induced precipitation of Aβ occurs as the pH falls below 7.0, comparable with conditions of acidosis (Yates, C.M., *et al.*, *J. Neurochem. 55*:1624 (1990)) in the AD brain. Investigation of the precipitating effects of a host or other metal ions in this system indicated that metal ion precipitation of Aβ was limited to copper and zinc, as illustrated, although Fe(II) possesses a partial capacity to induce precipitation (Bush, A.I., *et al.*, *Science 268*:1921 (1995)).

On the basis these *in vitro* findings, the possibility that Aβ deposits in the Ad-affected brain may be held in assembly by zinc and copper ions was investigated. Roher and colleagues have recently shown that much of the Aβ that deposits in Ad-affected cortex can be solubilized in water (Roher, A.E, *et al.*, *J. Biol. Chem. 271*:20631 (1996)). Supporting the clinical relevance of *in vitro* findings, it has recently been demonstrated that metal chelators increase the ~~amount of Aβ extracted by Roher's technique (in neutral saline buffer), and that~~ the extraction of Aβ is increased as the chelator employed has a higher affinity for zinc or copper (FIG. 8). Hence TPEN is highly efficient in extracting Aβ, as are TETA, and bathocuproene, EGTA and EDTA are less efficient, requiring

higher concentrations 91 mm) to achieve the same level of recovery as say, TPEN (5μM). Zinc and copper ions (5-50 μM) added back to the extracting solution abolish the recovery of Aμ (which is subsequently extracted by the SDS sample buffer in the pellet fraction of the centrifuged brain homogenate suspension), but Ca^{2+} and Mg^{2+} added back to the chelator-mediated extracts of Aβ cannot abolish Aβ resolubilization from Ad-affected tissue even when these metal ions are present in millimolar concentrations.

Importantly, atomic absorption spectrophotometry assays of the metal content of the chelator-mediated extracts confirms that Cu and Zn are co-released with Aβ by the chelators, along with lower concentrations of Fe. These data strongly indicate that Aβ deposits (probably of the amorphous type) are held together by Cu and Zn and may also contain Fe. Interestingly, Aβ is not extractable from control brain without the use of chelators. This suggests that metal-assembled Aβ deposits may be the earliest step in the evolution of Aβ plaque pathology.

These findings propelled further inquiries into chemistry of metal ion- Aβ interaction. The precipitating effects upon Aβ of Zn(II) and Cu(II) were found to be qualitatively different. Zn-mediated aggregation is reversible with chelation and is not associated with neurotoxicity in primary neuronal cell cultures, whereas Cu-mediated aggregation is accompanied by the slow formation of covalently-bonded SDS-resistant dimers and induction of neurotoxicity. These neurotoxic SDS-resistant dimers are similar to those described by Roher (Roher, A.E, *et al.*, *J. Biol. Chem.* *271*:20631 (1996)).

To accurately quantitate the effects of different metals and pH on Aß solubility, synthetic human $Aß_{1-40}$ (2.5 μM) was incubated (37°C) in the presence of metal ions at various pH for 30 min. The resultant aggregated particles were sedimented by centrifugation to permit determination of soluble $Aß_{1-40}$ in the supernatant. To determine the centrifugation time required to completely sediment the aggregated particles generated under these conditions, $Aß_{1-40}$ was incubated for 30 min at 37°C with no metal, Zn^{2+} (100μM), Cu^{2+} (100 μM) and

pH (5.5). Reaction mixtures were centrifuged at 10 000g for different times, or ultracentrifuged at 100 000g for 1 h. (FIG. 1). Figure 1 shows the proportion of soluble $A\beta_{1-40}$ remaining following centrifugation of reaction mixtures. $A\beta_{1-40}$ was incubated (30 min., 37 °C) with no metal, under acidic conditions (pH 5.5), Zn^{2+} (100 μM) or Cu^{2+} (100 μM), and centrifuged at 10 000*g* for different time intervals, or at 100,000*g* (ultracentrifuged) for 1 h for comparison. All data points are means ± SD, n = 3.

Given that conformational changes within the N-terminal domain of Aß are induced by modulating $[H^+]$ (Soto, C., *et al., J. Neurochem. 63*:1191-1198 (1994)), and that there is a metal (Zn^{2+}) binding domain in the same region, experiments were designed to determine whether there was a synergistic effect of pH on metal ion-induced Aß aggregation. $A\beta_{1-40}$ was incubated with different bioessential metal ions at pH 6.6, 6.8 and 7.4. The results are show in FIG. 2A, where "all metals" indicates incubation with a combination containing each metal ion at the nominated concentrations, concurrently. FIG. 2A shows the proportion of soluble $A\beta_{1-40}$ remaining in the supernatant after incubation (30 min., 37°C) with various metals ions at pH 6.6, 6.8 or 7.4 after centrifugation (10,000g, 20 min.),

The $[H^+]$ chosen represented the most extreme, yet physiologically plausible $[H^+]$ that $A\beta_{1-40}$ would be likely to encounter *in vivo*. The ability of different bioessential metal ions to aggregate $A\beta_{1-40}$ at increasing H^+ concentrations fell into two groups; Mg^{2+}, Ca^{2+}, Al^{3+}, Co^{2+}, Hg^{2+}, Fe^{3+}, Pb^{2+} and Cu^{2+} showed increasing sensitivity to induce $A\beta_{1-40}$ aggregation, while Fe^{2+}, Mn^{2+}, Ni^{2+}, and Zn^{2+} were insensitive to alterations in $[H^+]$ in their ability to aggregate $A\beta_{1-40}$. Cu^{2+} and Hg^{2+} induced most aggregation as the $[H^+]$ increased, although the $[H^+]$ insensitive Zn^{2+}-induced aggregation produced a similar amount of aggregation. Fe^{2+}, but not Fe^{3+}, also induced considerable aggregation as the $[H^+]$ increased, possibly reflecting increased aggregation as a result of increased crosslinking of the peptide.

Similar results were obtained when these experiments were repeated using turbidometry as an index of aggregation (FIG. 2B). The data indicate the absorbance changes between reaction mixtures with and without metal ions at pH 6.6, 6.8 or 7.4. Thus, Aß$_{1-40}$ has both a pH insensitive and a pH sensitive metal binding site. At higher concentrations of metal ions this pattern was repeated, except Co^{2+} and Al^{3+}-induced Aß aggregation became pH insensitive, and Mn became sensitive (FIG. 2C).

Since ^{64}Cu is impractically short-lived (t1/2 = 13 h), a novel metal-capture ELISA assay was used to perform competition analysis of Aß$_{1-40}$ binding to a microtiter plate impregnated with Cu^{2+}, as described in Materials and Methods. Results are shown in FIG. 3. All assays were performed in triplicate and are means ± SD, n=3. Competition analysis revealed that Aß$_{1-40}$ has at least one high affinity, saturable Cu^{2+} binding site with a Kd = 900 pM at pH 7.4 (FIG. 3). The affinity of Aß for Cu^{2+} is higher than that for Zn^{2+} (Bush, A.I., *et al., J. Biol. Chem. 269*:12152 (1994)). Since Cu^{2+} does not decrease Zn^{2+}-induced aggregation (Bush, A.I., *et al., J. Biol. Chem. 269*:12152 (1994)), indicating Cu^{2+} does not displace bound Zn^{2+}, there are likely to be two separate metal binding sites. This is supported by the fact that there is both a pH sensitive and insensitive interaction with different metal ions.

Since the conformational state and solubility of Aß is altered at different pH (Soto, C., *et al., J. Neurochem. 63*:1191-1198 (1994)), the effects of $[H^+]$ on Zn^{2+}- and Cu^{+}-induced Aß$_{1-40}$ aggregation were studied. Results are shown in FIGS. 4A, 4B and 4C. FIG. 4A shows the proportion of soluble Aß$_{1-40}$ remaining in the supernatant following incubation (30 min., 37°C) at pH 3.0-8.8 in buffered saline ± Zn^{2+} (30 µM) or Cu^{2+} (30 µM) and centrifugation (10 000g, 20 min.), expressed as a percentage of starting peptide. All data points are means ± SD, n=3. $[H^+]$ alone precipitates Aß$_{1-40}$ (2.5 µM) as the solution is lowered below pH 7.4, and dramatically once the pH falls below 6.3 (FIG. 4A). At pH 5.0, 80% of the peptide is precipitated, but the peptide is not aggregated by acidic environments below pH 5, confirming and extending earlier reports on the effect

of pH on Aß solubility (Burdick, D., *J. Biol. Chem.* 267:546-554 (1992)). Zn^{2+} (30 μM) induced a constant level (~50%) of aggregation between pH 6.2-8.5, while below pH 6.0, aggregation could be explained solely by the effect of [H^+].

In the presence of Cu^{2+} (30 μM), a decrease in pH from 8.8 to 7.4 induced a marked drop in Aß$_{1-40}$ solubility, while a slight decrease below pH 7.4 strikingly potentiated the effect of Cu^{2+} on the peptide's aggregation. Surprisingly, Cu^{2+}caused >85 % of the available peptide to aggregate by pH 6.8, a pH which plausibly represents a mildly acidotic environment. Thus, conformational changes in Aß brought about by small increases in [H^+] result in the unmasking of a second metal binding site that leads to its rapid self-aggregation. Below pH 5.0, the ability of both Zn^{2+} and Cu^{2+} to aggregate Aß was diminished, consistent with the fact that Zn binding to Aß is abolished below pH 6.0 (Bush, A.I., *et al., J. Biol. Chem. 269*:12152 (1994)), probably due to protonation of histidine residues.

The relationship between pH and Cu^{2+} on Aß$_{1-40}$solubility was then further defined by the following experiments (FIG. 4B). The proportion of soluble Aß$_{1-40}$ remaining in the supernatant after incubation (30 min., 37 °C) at pH 5.4-7.8 with different Cu^{2+} concentrations (0, 5, 10, 20, 30 μM), and centrifugation (10,000g, 20 min.), was measured andexpressed as a percentage of starting peptide. All data points are means ± SD, n=3. At pH 7.4, Cu^{2+}-induced Aß aggregation was 50% less than that induced by Zn^{2+}over the same concentration range, consistent withearlier reports (Bush, A.I., *et al., J. Biol. Chem. 269*:12152 (1994)). There was a potentiating relationship between [H^+] and [Cu^{2+}] in producing Aß aggregation; as the pH fell, less $Cu^{2+}$was required to induce the same level of aggregation, suggesting that [H^+] is controlling Cu^{2+} induced Aß$_{1-40}$ aggregation.

To confirm that this reaction occurs at physiological concentrations of Aß$_{1-40}$ and Cu^{2+}, a novel filtration immunodetection system was employed. This technique enabled the determination of the relative amount of Aß$_{1-40}$ aggregation in the presence of different concentrations of H^+ and Cu^{2+} (FIG. 4C). The relative aggregation of nM concentrations of Aß$_{1-40}$ at pH 7.4 and pH 6.6 in the presence

of different Cu^{2+} concentrations (0, 0.1, 0.2, 0.5 μM) were determined by this method. Data represent mean reflectance values of immunoblot densitometry expressed as a ratio of the signal obtained when the peptide is treated in the absence of Cu^{2+}. All data points are means ± SD, n = 2.

This sensitive technique confirmed that physiological concentrations of $A\beta_{1-40}$ are aggregated under mildly acidic conditions and that aggregation was greatly enhanced by the presence of Cu^{2+} at concentrations as low as 200 nM. Furthermore, as previously observed at higher $A\beta_{1-40}$ concentrations, a decrease in pH from 7.4 to 6.6 potentiated the effect of Cu^{2+} on aggregation of physiological concentrations of $A\beta_{1-40}$. Thus, $A\beta_{1-40}$ aggregation is concentration independent down to 8 nM where Cu^{2+} is available.

It has recently been shown that Zn^{2+} mediated $A\beta_{1-40}$ aggregation is reversible whereas $A\beta_{1-40}$ aggregation induced by pH 5.5 was irreversible (**57**). Therefore, we testedexperiments were performed to determine whether Cu^{2+}/pH-mediated $A\beta_{1-40}$ aggregation was reversible. Cu^{2+}-induced $A\beta_{1-40}$ aggregation at pH 7.4 was reversible following EDTA chelation, although for each new aggregation cycle, complete resolubilization of the aggregates required a longer incubation. This result suggested that a more complex aggregate is formed during each subsequent aggregation cycle, preventing the chelator access to remove Cu^{2+} from the peptide. This is supported by the fact that complete resolubilization occurs with time, and indicates that the peptide is not adopting a structural conformation that is insensitive to Cu^{2+}-induced aggregation/EDTA-resolubilization.

The reversibility of pH potentiated Cu^{2+}-induced $A\beta_{1-40}$ aggregation was studied by turbidometry between pH 7.5 to 6.6, representing H^+ concentration extremes that might be found *in vivo* (FIGS. 5A and 5B). Unlike the irreversible ~~aggregation of $A\beta_{1-40}$ observed at pH 5.5. Cu^{2+}-induced $A\beta_{1-40}$ aggregation was~~ fully reversible as the pH oscillated between pH 7.4 and 6.6. Figure 5A shows the turbidometric analysis of Cu^{2+}-induced $A\beta_{1-40}$ aggregation at pH 7.4 reversed by successive cycles of chelator (EDTA), as indicated. Figure 5B shows

turbidometric analysis of the reversibility of Cu^{2+}-induced $Aß_{1-40}$ as the pH cycles between 7.4 and 6.6. Thus, subtle conformational changes within the peptide induced by changing $[H^+]$ within a narrow pH window, that corresponds to physiologically plausible $[H^+]$, allows the aggregation or resolubilization of the peptide in the presence of Cu^{2+}.

Discussion

These results suggest that subtle conformational changes in Aß induced by $[H^+]$ promote the interaction of $Aß_{1-40}$ with metal ions, in particular $Cu^{2+}$and Hg^{2+} allowing self-aggregate or resolubilize depending on the $[H^+]$ (FIGs. 2A, 2B, 2C, 4A, 4B, 4C). A decrease in pH below 7.0 increases the ß-sheet conformation (Soto, C., *et al., J. Neurochem. 63*:1191-1198 (1994)), and this may allow the binding of Cu^{2+} to soluble Aß that could further alter the conformation of the peptide allowing for self aggregation, or simply help coordinate adjacent Aß molecules in the assembly of the peptides into aggregates. Conversely, increasing pH above 7.0 promotes the a-helical conformation (Soto, C., *et al., J. Neurochem. 63*:1191-1198 (1994)), which may alter the conformational state of the dimeric aggregated peptide, releasing Cu and thereby destabilizing the aggregate with the resultant release of Aß into solution. Thus, in the presence of Cu^{2+}, $Aß_{1-40}$ oscillates between an aggregated and soluble state dependent upon the $[H^+]$.

Interestingly, Hg^{2+} mediated Aß aggregation has greatly potentiated by mild acidity (FIG. 2C). $Aß_{1-40}$ aggregation by Co^{2+}, like Zn^{2+}, was pH insensitive and per mole induced a similar level of aggregation. Unlike Zn^{2+}, $Aß_{1-40}$ binding of Co^{2+} may be employed for the structural determination of the pH insensitive binding site given its nuclear magnetic cababilities.

The biphasic relationship of Aß solubility with pH mirrors the conformational changes previously observed by CD spectra within the N-terminal fragment (residues 1-28) of Aß (reviewed in (Soto, C., *et al., J. Neurochem.*

63:1191-1198 (1994)); a-helical between pH 1-4 and >7, but ß-sheet between pH 4-7. The irreversible aggregates of Aß formed at pH 5.5 supports the hypothesis that the ß-sheet conformation is a pathway for Aß aggregation into amyloid fibrils. Since aggregates produced by Zn^{2+} and Cu^{2+} under mildly acidic conditions (FIGs. 5A and 5B) are chelator/pH reversible, there conformation may be the higher energy a-helical conformation.

These results now indicate that there are three physiologically plausible conditions which could aggregate Aß: pH (FIGs. 1, 4A-4C; Fraser, P.E., *et al., Biophys. J. 60*:1190-1201 (1991); Barrow, C.J. and Zagorski, M.G., *Science 253*:179-182 (1991); Burdick, D., *J. Biol. Chem.* 267:546-554 (1992); Barrow, C.J., *et al., J. Mol. Biol. 225*:1075-1093 (1992); Zagorski, M.G. and Barrow, C.J., *Biochemistry 31*:5621-5631 (1992); Kirshenbaum, K. and Daggett, V., *Biochemistry 34*:7629-7639 (1995); Wood, S.J., *et al., J. Mol. Biol. 256*:870-877 (1996), [Zn^{2+}] (FIGs. 1, 2A and 2B, 4A-4C; Bush, A.I., *et al., J. Biol. Chem. 269*:12152 (1994); Bush, A.I., *et al., Science 265*:1464 (1994); Bush, A.I., *et al., Science 268*:1921 (1995); Wood, S.J., *et al., J. Mol. Biol. 256*:870-877 (1996))and under mildly acidic conditions, [Cu^{2+}] (FIGs. 2A, 4A-4C, 5B). Interestingly, changes in metal ion concentrations and pH are common features of the inflammatory response to injury. Therefore, the binding of Cu^{2+} and Zn^{2+} to Aß may be of particular importance during inflammatory processes, since local sites of inflammation can become acidic (Trehauf, P.S. and McCarty, D.J., *Arthr. Rheum. 14*:475-484 (1971); Menkin, V., *Am. J. Pathol. 10*:193-210 (1934)) and both Zn^{2+} and Cu^{2+} are rapidly mobilized in response to inflammation (Lindeman, R.D., *et al., J. Lab. Clin. Med. 81*:194-204 (1973); Terhune, M.W. and Sandstead, H.H., *Science 177*:68-69 (1972); Hsu, J.M., *et al., J. Nutrition 99*:425-432 (1969); Haley, J.V., *J. Surg. Res. 27*:168-174 (1979); Milaninio, R., *et al., Advances in Inflammation Research 1*:281-291 (1979); Frieden, E., in *Inflammatory Diseases and Copper*, Sorenson, J.R.J., ed, Humana Press, New Jersey (1980), pp. 159-169).

Serum copper levels increase during inflammation, associated with increases in ceruloplasmin, a Cu^{2+} transporting protein that may donate Cu^{2+} to enzymes active in processes of basic metabolism and wound healing such as cytochrome oxidase and lysyl oxidase (Giampaolo, V., *et al.*, in *Inflammatory Diseases and Copper*, Sorenson, J.R.J., ed, Humana Press, New Jersey (1980), pp. 329-345; Peacock, E.E. and vanWinkle, W., in *Wound Repair*, W.B. Saunders Co., Philadelphia (1976), pp. 145-155)). Since the release of Cu^{2+} from ceruloplasmin is greatly facilitated by acidic environments where the cupric ion is reduced to its cuprous form (Owen, C.A., Jr., *Proc. Soc. Exp. Biol. Med. 149*:681-682 (1975)), periods of mild acidosis may promote an environment of increased free Cu^{2+}. Similarily, aggregation of another amyloid protein, the acute phase reactant serum amyloid P component (SAP) to the cell wall polysaccharide, zymosan, has been observed with Cu^{2+} at acidic pH (Potempa, L.A., *et al., Journal of Biological Chemistry 260*:12142-12147 (1985)). Thus, exchange of Cu^{2+} to $Aß_{1-40}$ during times of decreased pH may provide a mechanism for altering the biochemical reactivity of the protein required by the cell under mildly acidic conditions. Such a function may involve alterations in the aggregation/adhesive properties (FIGS. 1-5B) or oxidative functions of Aß at local sites of inflammation.

While the pathogenic nature of $Aß_{1-42}$ in AD is well described (Maury, C.P.J., *Lab. Investig. 72*:4-16 (1995); Multhaup, G., *et al., Nature 325*:733-736 (1987)), the function of the smaller $Aß_{1-40}$ remains unclear. The present data suggest that Cu^{2+}-binding and aggregation of Aß will occur when the pH of the microenvironment rises. This conclusion can be based on the finding that the reaction is $[H^+]$ and $[Cu^{2}]$ dependent and reversible within a narrow, physiologically plausible, pH window. This is further supported by the specificity and high affinity of Cu^{2+} binding under mildly acidic conditions compared to the constant Zn^{2+}-induced aggregation (and binding) of $Aß_{1-40}$ over a wide pH range (6.2-8.5). The brain contains high levels of both Zn^{2+} (~150 μM; Frederickson, C.J. *International Review of Neurobiology* 31:145-237 (1989)) and Cu^{2+} (~100

μM; Warren, P.J., *et al., Brain 83*:709-717 (1960); Owen, C.A., *Physiological Aspects of Copper*, Noyes Publications, Park Ridge, New Jersey (1982), pp160-191). Intracellular concentrations are approximately 1000 and 100 fold higher than extracellular concentrations. This large gradient between intracellular and extracellular compartments suggests a highly energy dependent mechanism is required in order to sequester these metals within neurons. Therefore, any alterations in energy metabolism, or injury, may affect the reuptake of these metal ions and promote there release into the extracellular space, and together with the synergistic affects of decreased pH (see above) induce membrane bound $Aß_{1-40}$ to aggregate. Since increased concentrations of Zn^{2+} and Cu^{2+}, and decreased pH, are common features of all forms of cellular insult, the initiation of $Aß_{1-40}$ function likely occurs in a coordinated fashion to alter adhesive and/or oxidative properties of this membrane protein essential for maintaining cell integrity and viability. That $Aß_{1-40}$ has such a high affinity for these metal ions, indicates a protein that has evolved to respond to slight changes in the concentration of extracellular metal ions. This is supported by the fact that aggregation in the presence of Cu is approx. 30% at pH 7.1, the pH of the brain (Yates CM, *et al., J. Neurochem. 55*:1624-1630 (1990)), but 85% at pH 6.8. Taken together, our present results indicate that $Aß_{1-40}$ may have evolved to respond to biochemical changes associated with neuronal damage as part of the locally mediated response to inflammation or cell injury. Thus, it is possible that Cu^{2+} mediated $Aß_{1-40}$ binding and aggregation might be a purposive cellular response to an environment of mild acidosis.

The deposition of amyloid systemically is usually associated with an inflammatory response (Pepys, M.B. and Baltz, M.L., *Adv. Immunol. 34*:141-212 (1983); Cohen, A.S., in *Arthritis and Allied Conditions*, D.J. McCarty, ed., Lea ~~and Febiger, Philadelphia (1989), pp. 1273-1293; Kisilevsky, R., *Lab. Investig.*~~ *49*:381-390 (1983)). For example, serum amyloid A, one of the major acute phase reactant proteins that is elevated during inflammation, is the precursor of amyloid A protein that is deposited in various tissues during chronic

inflammation, leading to secondary amyloidosis (Gorevic, P.D., *et al., Ann. NY Acad. Sci.*:380-393 (1982)). An involvement of inflammatory mechanisms has been suggested as contributing to plaque formation in AD (Kisilevsky, R., *Mol. Neurobiol. 49*:65-66 (1994)). Acute-phase proteins such as alpha 1-antichymotrypsin and c-reactive protein, elements of the complement system and activated microglial and astroglial cells are consistently found in AD brains.

The rapid appearance, within days of Aß deposits and APP immunoreactivity following head injury (Roberts, G. W., *et al., Lancet. 338*:1422-1423 (1991); Pierce, J.E.S., *et al., Journal of Neuroscience 16*:1083-1090 (1996)), rather than the more gradual accumulation of Aß into more dense core amyloid plaques over months or years in AD may be compatible with the release of Zn^{2+}, Cu^{2+} and mild acidosis in this time frame. Thus, pH/metal ion mediated aggregation may form the basis for the amorphous Aß deposits observed in the aging brain and following head injury, allowing the maintenance of endothelial and neuronal integrity while limiting the oxidative stress associated with injury that may lead to a diminishment of structural function.

Since decreased cerebral pH is a complication of aging (Yates CM, *et al., J. Neurochem. 55*:1624-1630 (1990)), these data indicate that Cu and Zn mediated Aß aggregation may be a normal cellular response to an environment of mild acidosis. However, prolonged exposure of Aß to an environment of lowered cerebral pH may promote increased concentrations of free metal ions and reactive oxygen species, and the inappropriate interaction of Aß$_{1-42}$ over time promoting the formation of irreversible Aß oligomers and it's subsequent deposition as amyloid in AD. The reversibility of this pH mediated Cu^{2+} aggregation does however present the potential for therapeutic intervention. Thus, cerebral alkalinization may be explored as a therapeutic modality for the ~~reversibility of amyloid deposition *in vivo*.~~

Example 2

Free Radical Formation and SOD-like activity of Alzheimer's Aβ Peptides

a) Determination of Cu^{+} and Fe^{2+}

This method is modified from a protocol assaying serum copper and iron (Landers, J.W. and Zak, B., Am. J. Clin. Pathol ~~*Chim. Acta*~~ *29*:590 (1958)). It is based on the fact that there are optimal visible absorption wavelengths of 483 nm and 535 nm for Cu^{+} complexed with bathocuproinedisulfonic (BC) anion and Fe^{2+} coordinated by bathophenanthrolinedisulfonic (BP) anion, respectively.

Determination of molar absorption of these two complexes was accomplished essentially as follows. An aliquot of 500 μl of each complex (500 μM, in PBS pH 7.4, with ligands in excess) was pipetted into 1 cm-pathlength quartz cuvette, and their absorbances were measured. Their molar absorbancy was determined based on Beer-Lambert's Law. Cu^{+}-BC has a molar absorbancy of 2762 M^{-1} cm^{-1}, while Fe^{2+}-BP has a molar absorbancy of 7124 M^{-1} cm^{-1}.

Determination of the equivalent vertical pathlength for Cu^{+}-BC and Fe^{2+}-BP in a 96-well plate was carried out essentially as follows. Absorbances of the two complexes with a 500 μM, 100 μM, 50 μM, and 10 μM concentration of relevant metal ions (Cu^{+}, Fe^{2+}) were determined both by 96-well plate readers (300 μL) and UV-vis spectrometer (500 μL), with PBS, pH 7.4, as the control blank. The resulting absorbancies from the plate reader regress against absorbancies by a UV-vis spectrometer. The slope k from the linear regression line is equivalent to the vertical pathlength if the measurement is carried out on a plate. The results are:

	k(cm)	r^2
Cu^{+}-BC	1.049	0.998
Fe^{2+}-BP	0.856	0.999

With molar absorbancy and equivalent vertical pathlength in hand, the concentrations (μM) of Cu^+ or Fe^{2+} can be deduced based on Beer-Lambert's Law, using proper buffers as controls.

$$\text{for } Cu^+: \; [Cu^+]\ (\mu M) = \frac{\Delta A(483nm)}{(2762 \ x \ 1.049)} \ x \ 10^6$$

$$\text{for } Fe^{2+}: \; [Fe^{2+}]\ (\mu M) = \frac{\Delta A \ (535nm)}{(7124 \ x \ 0.856)} \ x \ 10^6$$

where ΔA is absorbancy difference between sample and control blank.

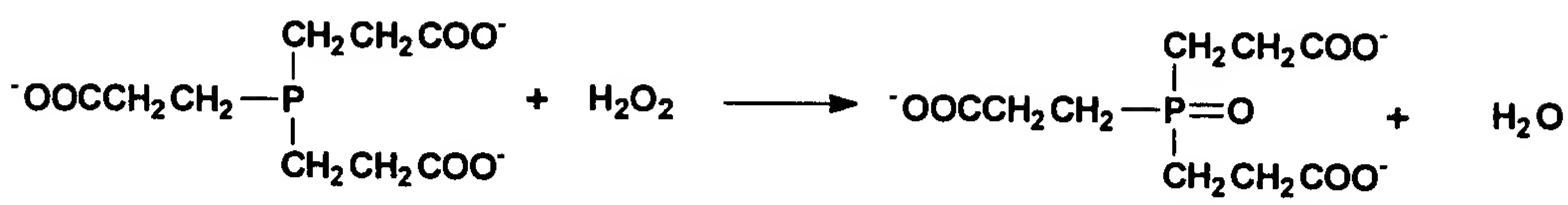
b) Determination of H_2O_2

This method is modified from a H_2O_2 assay reported recently (Han, J.C. *et al., Anal. Biochem. 234*:107 (1996)). The advantages of this modified H_2O_2 assay on 96-well plate include high throughput, excellent sensitivity (~1 μM), and the elimination of the need for a standard curve of H_2O_2 , which is problematic due to the labile chemical property of H_2O_2.

Aβ peptides were co-incubated with a H_2O_2-trapping reagent (Tris(2-carboxyethyl)-phosphine hydrochloride, TCEP, 100 μM) in PBS (pH 7.4 or 7.0) at 37°C for 30 mins. Then 5,5′-dithio-bis(2-nitrobenzoic acid) (DBTNB, 100 μM) was added to react with remaining TCEP. The product of this reaction has a characteristic absorbance maximum of 412 nm [18]. The assay was adapted to a 96-well format using a standard absorbance range (see FIG. 11).

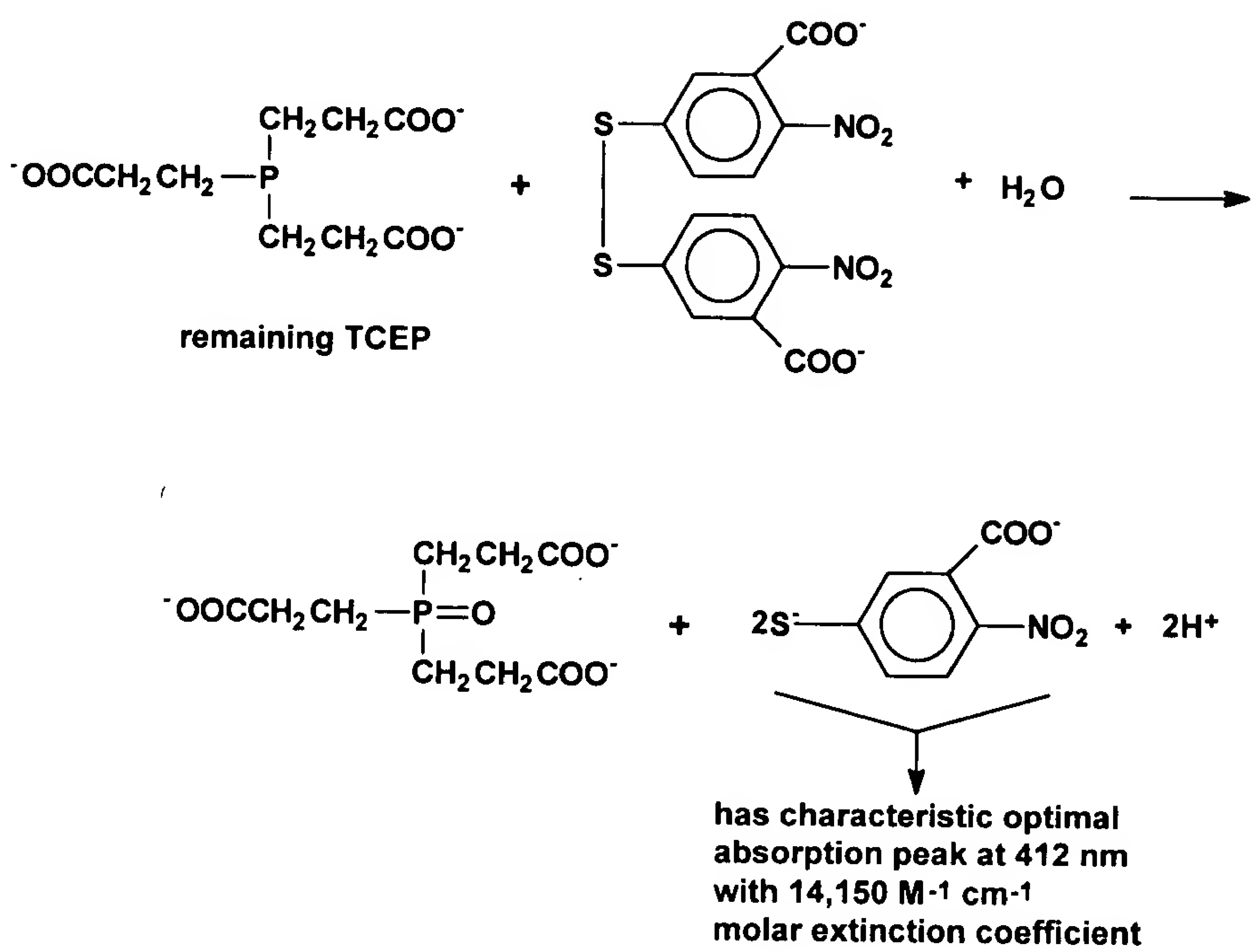
The chemical scheme for this novel method is:

Scheme I:



(TCEP) [Tris (2-carboxethyl) phosphine]

Scheme II:



TCEP•HCl was synthesized by hydrolyzing tris (2-cyno-ethyl) phosphine (purchased from Johnson-Mathey (Waydhill, MA)), in refluxing aqueous HCl (Burns, J.A. *et al.*, *J. Org. Chem.* *56*:2648 (1991)) as shown below.

$$(NCCH_2CH_2)_3P \xrightarrow[\text{reflux}]{\text{aq HCl}} \underset{TCEP \cdot HCl}{(HO_2CCH_2CH_2)_3\,PH^+Cl^-}$$

In order to carry out the above-described assay in a 96-well plate, it was necessary to calculate the equivalent vertical pathlength of 2-nitro-5-thiobenzoic acid (TMB) in a 96-well plate. This determination was carried out essentially as described for Cu^{+}-BC and Fe^{2+}-BP in Example 5. The resulting absorbancies from the plate reader regress against absorbancies by a UV-vis spectrometer. The slope k from the linear regression line is equivalent to the vertical pathlength if the measurement is carried out on a plate. The results are:

k	r2
0.875	1.00

The concentration of H_2O_2 can then be deduced from the difference in absorbance between the sample and the control (sample plus 1000 U/µl catalase)

$$[H_2O_2]\ (\mu M) = \frac{\Delta A\ (412nm)}{(2\ x\ 0.875\ x\ 14150)}$$

c) Determination of OH·

Determination of OH· was performed as described in Gutteridge *et al.* (*Biochim. Biophys. Acta 759*: 38-41 (1983)).

d) Cu(I) generation by Aβ: influence of Zn(II) and pH

Aβ (10 µM in PBS, pH 7.4 or 6.8, as shown) was incubated for 30 minutes (37°C) in the presence of Cu(II) 10 µM ± Zn(II) 10 µM). Cu(I) levels (n=3, ±SD) were assayed against a standard curve. These data indicate that the presence of Zn(II) can mediate the reduction of Cu(II) in a mildly acidic environment. The effects of zinc upon these reactions are strongly in evidence

but complex. Since the presence of 10 μM zinc will precipitate the peptide, it is clear that the peptide possesses redox activity even when it is not in the soluble phase, suggesting that cortical Aβ deposits will not be inert in terms of generating these highly reactive products. Cerebral zinc metabolism is deregulated in AD, and therefore levels of interstitial zinc may play an important role in adjusting the Cu(I) and H_2O_2 production generated by Aβ. The rat homologue of Aβ1→40 does not manifest the redox reactivity of the human equivalent. Insulin, a histidine-containing peptide that can bind copper aind zinc, exhibits no Cu(II) reduction.

e) ***Hydrogen peroxide production by Aβ species***

$AB_{1\text{-}42}$ (10 μM) was incubated for 1 hr at 37°C, pH 7.4 in ambient air (first bar), continuous argon purging (Ar), continuous oxygen enrichment (O_2) at pH 7.0 (7.0), or in the presence of the iron chelator desferioxamine (220 μM; DFO). Variant Aβ species (10 μM) were tested: $A\beta_{1\text{-}40}$ ($A\beta_{1\text{-}40}$), rat $A\beta_{1\text{-}40}$ (rAβ1→40), and scrambled Aβ1→40 ($sA\beta_{1\text{-}40}$) were incubated for 1 hr at 37°C, pH 7.4 in ambient air. Values (mean ±SD, n=3) represent triplicate samples minus values derived from control samples run under identical conditions in the presence of catalase (10 U/ml). The details of the experiment are as follows: Aβ peptides were co-incubated with a H_2O_2-trapping reagent (Tris(2-carboxyethyl)-phosphine hydrochloride, TCEP, 100 μM) in PBS (pH 7.4 or 7.0) at 37°C for 30 mins. Then 5,5′-dithio-bis(2-nitrobenzoic acid) (DTNB, 100 μM) was added to react with remaining TCEP, the product has a characteristic absorbance maximum of 412 nm. The assay was adapted to a 96-well format using a standard absorbance range.

Results and Discussion

Aβ exhibits metal-dependent and independent redox activity

Because Aβ was observed to be covalently linked by Cu, the ability of the peptide to reduce metals and generate hydroxyl radicals was studied. The bathocuproine and bathophenanthroline reduced metal assay technique employed by Multhaup *et al.* was used in order to determine that APP itself possesses a Cu(II) reducing site on its ectodomain (Multhaup, G., *et al.*, *Science 271*:1406 (1996)). It has been discovered that Aβ possesses a striking ability to reduce both Fe(III) to Fe(II), and Cu(II) to Cu(I), modulated by Zn(II) and pH (6.6-7,4) (FIG. 10). It is of great interest that the relative redox activity of the peptides studied correlates so well with their relative pathogenicity viz Aβ42>Aβ40>ratAβ in all redox assays studied. Since one of the caveats in using the reduced metals assay is that the detection agents can exaggerate the oxidation potential of Cu(II) or Fe (III), other redox products were explored by assays where no metal ion indicators were necessary. It was discovered that hydrogen peroxide was rapidly formed by Aβ species (FIG. 11). Thus, Aβ produces both H_2O_2 and reduced metals whilst also binding zinc. Structurally, this is difficult to envisage for a small peptide, but we have recently shown that Aβ is dimeric in physiological buffers. Since H_2O_2 and reduced metal species are produced in the same vicinity, these reaction products are liable to produce the highly toxic hydroxyl radical by Fenton chemistry, and the formation of hydroxyl radicals from these peptides has now been shown with the thiobarbituric acid assay. The formation of hydroxyl radicals correlates with the covalent polymerization of the peptide (FIG. 9) and can be blocked by hydroxyl scavengers. Thus the concentrations of Fe, Cu, Zn & H+ in the brain interstitial milliu could be important in facilitating precipitation and neurotoxicity for Aβ by direct (dimer formation) and indirect (Fe(II)/Cu(I) and H_2O_2 formation) mechanisms.

H_2O_2 production by Aβ explains the mechanism by which H_2O_2 has been described to mediate neurotoxicity (Behl, C., *et al.*, *Cell 77*:827 (1994)),

previously thought to be the product of cellular overproduction alone. Interestingly, the scrambled Aβ peptide produces appreciable H_2O_2 (FIG. 6) but no hydroxyl radicals. This is because the scrambled Aβ peptide is unable to reduce metal ions. Therefore, we conclude that what makes Aβ such a potent neurotoxin is its capacity to produce both reduced metal sand H_2O_2 at the same time. This "double whammy" can then produce hydroxyl radicals by the Fenton reaction, especially if the H_2O_2 is not rapidly removed from the vicinity of the peptide. Catalase and glutathione peroxidase are the principal means of catabolizing H_2O_2, and their levels are low in the brain, especially in AD, perhaps explaining the propensity of Aβ to accumulate in brain tissue.

FIG. 11 shows that the production of H_2O_2 is oxygen dependent, and further investigation has indicated that Aβ can spontaneously produce the superoxide radical (O_2^-) in the absence of metal ions. This property of Aβ is particularly exaggerated in the case of Aβ42, probably explaining why this peptide is more neurotoxic and more enriched than Aβ40 in amyloid. O_2^- generation will be subject to spontaneous dismutation to generate H_2O_2, however, this is a relatively slow reaction, although it may account for the majority of the H_2O_2 detected in our Aβ assays. O_2^- is reactive, and the function of superoxide dismutase (SOD) is to accelerate the dismutation to produce H_2O_2 which is then catabolized by catalase and peroxidases into oxygen and water. The most abundant form of SOD is Cu/Zn SOD, mutations of which cause another neurodegenerative disease, amyotrophic lateral sclerosis (Rosen, D., *et al.*, *Nature 364*:362 (1993)). Since Aβ, like Cu/Zn SOD, is a dimeric protein that binds Cu and Zn and reduces Cu(II) and Fe(III), we studied the O_2^- dismutaion behavior of Aβ in the μsec time-scale using laser pulse photolysis. These experimetns have shown that Aβ exhibits Fe/Cu-dependent SOD-like activity with rate constants ~~of dismutation at ≈10^8 M^{-1} sec^{-1}, which are strikingly similar to SOD. Hence, Aβ~~ appears to be a good candidate to possess the same function as SOD, and therefore may function as an antioxidant. This may explain why oxidative stresses cause it to be released by cells (Frederikse, P.H., *et al.*, *Journal of*